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Methodological proposals for improved assessments of the impact of traffic noise upon human health

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Abstract
Background, aim and scope Several methodological shortcomings still hinder the inclusion of transport noise as an established impact category within life cycle assessment (LCA). Earlier attempts to quantify the health damages caused by traffic noise yielded valuable results from an academic point of view, but these were of limited use in the context of everyday LCA practice. An enhanced understanding of traffic noise emission models coupled with a straightforward choice of indicators could lead to faster, more accurate assessments of health impairment due to traffic noise whose results would fittingly serve the purposes of policy makers and the information needs of the general public alike. This article aims to propose the guidelines for such assessments.
Materials and methods The assessment method presented takes an incremental approach in similar fashion as previous work in the field done by R. Müller-Wenk. An explanation is provided of how the assumption of linearity leads to a substantial overestimation of noise level increments attributable to additional vehicles, and subsequently to a misjudgement of overall health impacts due to traffic noise. Hence, an alternative calculation method allowing for better accuracy in the computation of noise level increments is proposed. This method can be easily applied, needless of a specific traffic noise emission model. A more detailed method, based on the state-of-the-art Improved Methods for the Assessment of the Generic Impact of Noise in the Environment (IMAGINE) traffic noise emission model, is also described. This method is to be applied to large-, medium- and small-scale assessments where variations in traffic flow or composition can be reasonably predicted or measured. In the proposed methodology, health impairment due to traffic noise is not aggregated in DALY (disability-adjusted life years). Rather, the results are given in terms of the 'number of annoyed persons', which is derived from the synthesis curves relating noise exposure to annoyance presented by Miedema and Oudshoorn. The calculation procedure and data needs to do this are explained. Moreover, the validity of taking the number of annoyed persons as a proxy for overall health impairment due to traffic noise—and the main benefits of doing so—are discussed. Performing the attribution of impacts on a per vehicle-kilometre basis can lead to impact misrepresentations whenever an incremental approach is taken. A different attribution scheme, which takes background noise into account, is thus proposed.
Results The general framework of a method to assess the impact of traffic noise upon human health within LCA is presented. This method, which finds its basis in the work of Müller-Wenk, can be used to evaluate a large number of variations in traffic other than mere increases in overall traffic flows. An application example evaluating the impact of a generic 1,000-km trip of a heavy-duty vehicle through Spain is provided in Section 2.4.
Discussion The incremental approach seems most adequate for the assessment of the impact of traffic noise upon human health within LCA, albeit the assumption of linearity can significantly distort its results. Likewise, performing the attribution of impacts through generic

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characterisations of additional vehicle-kilometres may mask the true responsibility of traffic for increasing noise levels, and is therefore advised against. The special characteristics of noise as a pollutant (relevance of spatial data, human perception issues) appear to justify the adoption of a distinct indicator, namely 'number of annoyed persons'.

Conclusions Reasonably good estimates of equivalent noise level increases due to proportional increases over pre-existing traffic can be given without using a noise emission model. Yet, the use of state-of-the-art vehicle noise emission models (e.g. IMAGINE) should allow for more accurate assessments, provided sufficient data regarding the spatial distribution of receivers and traffic characteristics (traffic flow, average speed per vehicle type and so forth) are known. Incorporating annoyance as the preferred indicator for the impact of traffic noise upon human health would make assessment results more intelligible and readily applicable to decision making in matters like infrastructure policing and urban planning, whilst placing the focus on damage prevention.

Recommendations and perspectives In this paper, only road traffic noise is dealt with. However, annoyance curves with a comparably solid scientific background also exist for railway and aircraft noise, which would make comparisons between alternative transportation modes feasible. The use of 'number of annoyed persons' instead of DALY units is favoured because it allows for a more straightforward presentation of results, even if it excludes the possibility of aggregation with other health impacts. Nevertheless, the use of DALY is not excluded beforehand, insofar as a scientifically sound relationship between long-term exposure to environmental noise and more severe health conditions is agreed upon by medical experts.

Keywords Annoyance · DALY (disability-adjusted life years) · LCA · Noise impact assessment · Road traffic noise

1 Background, aim and scope

Noise is universally perceived as a negative factor affecting human well-being. Noise sources plague everyday activities, making life less pleasurable and slowly eroding overall health in ways that are difficult to observe in the short term.

Road transport of passengers and goods is inextricably associated to human activities. It is also arguably the main source of intrusive sound emissions (EEA, 2007), both in terms of total sound power emitted and geographical distribution—which is practically akin to that of human population in modern societies. Unfortunately, several methodological shortcomings (complex problematic selection of health effects and dose-effect relations, non-linearity of impacts) still hinder the inclusion of transport noise as an established impact category within life cycle assessment (LCA).

Earlier attempts to quantify the health damages caused by traffic noise yielded valuable results from an academic point of view. In this respect, the work of Müller-Wenk (1999, 2002, 2004) is especially noteworthy since he was first to establish a complete cause-and-effect chain allowing to link a road transportation event to its health impacts, which were then quantitatively determined. In this way, the author managed to calculate the health burdens (in terms of communication and sleep disturbance) associated with all road traffic in Switzerland for the year 1995 and compute them in DALY (disability-adjusted life years). This methodology, if remarkably ingenious and apt to bring noise and life cycle thinking closer whilst raising awareness on the relevance of noise as a major source of global health impairment, shows limited applicability in the context of everyday LCA practice, where assessments of countrywide systems are seldom performed. Moreover, as will be discussed later, it is reliant upon simplifications leading to inaccuracies that would best be avoided.

An enhanced understanding of traffic noise emission models could lead to faster, more accurate assessments of health impairment due to traffic noise. The state-of-the-art Improved Methods for the Assessment of the Generic Impact of Noise in the Environment (IMAGINE) traffic noise emission model (IMAGINE 2005, 2007a, 2007b) is used herein for illustrative purposes; other models, however, could be analogously applied.

Earlier quantifications of health damages attributed to traffic noise (Doka 2003; Müller-Wenk 1999, 2002, 2004) were made in terms of DALY units. In this article, self-reported annoyance is proposed instead as the primary indicator for health impairment due to traffic noise. This straightforward use of indicators termed in plain, natural language (e.g. '[additional] number of persons annoyed by noise') has the benefit of presenting results in a manner that is intelligible to both policymakers and the general public, while being comparably effective in communicating the impacts of noise.

2 Materials and methods

2.1 Method overview

The assessment method presented herein adopts an incremental approach in similar fashion as previous work in the field done by Müller-Wenk (1999, 2002, 2004), wherein equivalent noise level increases attributable to additional vehicle-kilometres travelled throughout the whole road

network of Switzerland were approximated. This clever approach is also adopted in Doka (2003) and Althaus et al. (2009a, b), and is considered to be the most suitable for the inclusion of traffic noise assessments in LCA. For the sake of terminological accuracy, the general approach of the method we are proposing should rather be labelled as 'variational', since it allows for the assessment of different changes in several variables having an influence on noise emissions other than a small increase in the total of vehicle-kilometres (vkm) driven. This, as will be explained later, is accomplished by means of the implementation of a sophisticated traffic noise emission model into assessments.

The general framework of the method is as follows: the system under assessment—whose nature can be diverse—must be such that it produces a measurable influence over traffic conditions in a given physical environment. Traffic noise in this environment is assessed and modelled in both its initial (occurring in the absence of the system) and final conditions (occurring while the system is in operation), and the corresponding results are subtracted to yield variations—typically increments—in equivalent noise emission levels attributable to the presence of the system under assessment. These variations in equivalent noise levels are then transformed into health impacts using an appropriate health damage model. Finally, health impacts are attributed by means of an impact attribution function or scheme whose significance is not to be neglected. We note that in the proposed methodology, health impairment due to traffic noise is not aggregated in DALY. Rather, the results are given in terms of the 'number of annoyed persons', which is derived from the synthesis dose-response curves relating noise and annoyance presented by Miedema and Oudshoorn (2001).

2.2 Noise-relevant life cycle variations

A vast array of systems can be subject to the type of traffic noise assessment described herein. The single most important requirement for a system to be fit for being assessed with this methodology is that it should produce a number of noise-relevant life cycle variations (henceforth, NRLVs) affecting a 'traffic noise environment' associated with the system. A possible definition of NRLV would be 'whatever change in the noise environment of a system subject to LCA caused by the presence of the system itself'. Conversely, in the context of traffic noise assessments within LCA, 'traffic noise environment' would refer to 'a populated stretch of land of any given extension where road transport is the main source of environmental noise, while being also influenced by the system subject to LCA in some identifiable way'. The preceding definitions hint at the relevance attached to spatial data in this type of assessment, which will be further discussed later. In Table 1, examples of systems that may subject to the type of traffic noise assessment being described are provided, along with their traffic noise environment and example NRLVs.

Assessing variations in traffic noise using sound-measuring equipment (e.g. with integrating–averaging sound metres at selected locations) would be impractical and expensive, even at a fine geographical scale. A suitable traffic noise emission model is therefore needed to obtain the calculated traffic noise levels. These models are usually coupled to a mathematical sound propagation model, which can be implemented in computer software for calculation purposes. As will be justified later, incremental assessments can do without such a propagation model in most situations, thus greatly simplifying our task.

State-of-the-art traffic noise emission models reproduce the mean sound emission characteristics of different vehicle types or classes, which are built from actual sound measurements performed in laboratories and test tracks under reference conditions. These emission characteristics can be combined with traffic data (speeds, traffic composition, vehicle flows and so forth) to transform the sound power output of individual, moving vehicles into an equivalent line source, emitting the sound power of the traffic flow being modelled. State-of-the-art traffic noise emission models generate large amounts of 'raw' noise data (cf. Section 2.2.5), which have to be transformed into a manageable noise indicator. Consequently, some of the most critical stages in the assessment will be the collection of adequate data to model traffic conditions and the selection of appropriate noise metrics, which are discussed next.

2.2.1 Noise metrics and data requirements for assessments

European Directive 2002/49/EC relating to the assessment and management of environmental noise (EuP 2002) proposes L_{den} as the primary indicator for the evaluation of environmental noise. L_{den} (day-evening-night equivalent level) represents the annual average of noise determined over 24-h periods. The formula for this indicator is given in Eq. 1, where L_{day}, L_{evening} and L_{night} are the A-weighted long-term average sound level as defined in ISO 1996-2: 1987 (1987), determined respectively over all the day (12 h), evening (4 h) and night (8 h) periods of a representative year.

$$L_{\text{den}} = 10 \cdot \log_{10}\left[\frac{12}{24} \cdot 10^{L_{\text{day}}/10} + \frac{4}{24} \cdot 10^{(L_{\text{evening}}+5)/10} + \frac{8}{24} \cdot 10^{(L_{\text{night}}+10)/10}\right] \tag{1}$$

Selecting L_{den} as the primary environmental noise descriptor has important implications regarding which traffic data is needed to perform the assessment (in theory noise emissions should be characterized at different moments in a 24-h period). It also has some major advantages: pursuant to

Table 1 Examples of systems under assessment (see examples of NRLVs and noise environment)

System subject to assessment	Examples of potential NRLVs [*example of identification/characterization method*]	Traffic noise environment
Product or service that involves some form of road transport along its life cycle	Heavy-duty or light-duty vehicle traffic through national road network is increased. [*the total number of vehicle-kilometres travelled by heavy-duty vehicles over the national road system considered increases according to the transportation events associated with the life cycle of the product. The increased vehicle-kilometres may be apportioned based upon initial traffic flows]*	Surrounding area alongside national road system
Large industrial facility (e.g. port or fulfilment centre)	Heavy vehicle traffic through existing road is increased [*the output of the facility in tones is divided by the mean capacity of a truck to estimate additional outbound heavy vehicle traffic. Inbound (unloaded) traffic is also considered*] A new, dedicated road segment is constructed to service the facility (see NRLVs for 'New Road A')	Vicinity of road segment(s) affected by increased heavy vehicle traffic
New road A	Equivalent noise levels nearby new road A are increased due to traffic (initial situation was background noise only) [*background noise is measured –either before or after road A is constructed- using a statistical noise descriptor such as L_{90}; traffic is characterized through measurements at representative times of the day*][a]. Global traffic through previously existing road B -for which new road A is an alternative- decreases [*an estimated percentage of traffic is allocated from existing road B to new road A*]	Surrounding area alongside new road A where equivalent noise levels exceed those found in initial situation due to traffic noise
Existing road B	Global traffic through road B noise increased after a lane is added [*traffic data are obtained from toll gates; vehicle flows are broken down by cars/heavy vehicles*] Average vehicle speed on road B decreases (increases) after speed limit is lowered (raised) [*based upon relevant studies on traffic behaviour, mean speed for cars and motorcycles is assumed to be lowered (raised) by the same amount as the speed limit and to stay unchanged for heavy vehicles*]	Surrounding area alongside existing road B
National vehicle fleet	Yearly increase in global traffic [*an estimate is derived from data regarding vehicle sales and disposals*] Increased proportion of Diesel vehicles [*data regarding national vehicle fleet characteristics are used directly, e.g. within a LCA comparing the impact of Diesel and Otto cycle cars*]	Surrounding area alongside national road system
New type of tire compound	Decreases in noise level emissions due to a given percentage of cars fitted with new tires (marketed countrywide) [*the percentage of vehicles fitted with new type of tires is estimated from sales figures*]	Vicinity of roads throughout national road network
New type of low-noise road surface	Changes in noise emission characteristics after roads are repaved [*changes are predicted using test results provided by an independent acoustic laboratory*]	Vicinity of road segment(s) repaved

[a] Note that in this case noise increments will not be equal for all receivers, and a noise propagation model will be required

Directive 2002/49/EC and no later than 30 June 2012—and thereafter every 5 years—EU member states are to develop strategic noise maps of all the agglomerations with more than 100,000 inhabitants and of all the major roads and railways within their territories, showing the situation during the preceding year. Since it is required that these maps include at least L_{den} and L_{night} indicator results, the availability of spatial noise data featuring L_{den} levels can be expected to improve vastly in the years to come.

The data required for traffic noise assessments may be divided into two large blocks, namely traffic data and receiver data.

The following *traffic data* (listed in order of importance) are the most relevant to the accuracy of the noise calculations (IMAGINE 2007a): vehicle speeds and traffic composition, vehicle flows, instant acceleration or deceleration, speed distributions and data regarding the aforementioned parameters on low flow roads. Note that the availability of these data may be uneven. In an LCA context, a very fine simulation of traffic is not intended and typically only vehicle speeds, traffic composition (by vehicle class) and vehicle flows will be considered. These data can be obtained either directly (where data regarding vehicle flows and percentages of heavy vehicles in representative roads are routinely collected by organisations in charge of road infrastructure) or through well-reasoned assumptions (e.g. taking the generic speed limit in the corresponding road type as the mean speed, or estimating the allocation of traffic to periods of the day).

Receiver data are those data needed to calculate the impact of traffic noise variations to the receivers. These data sets may include one or more the following:

1. A spatially delimited traffic noise environment. In the method proposed herein, the typical traffic noise environment would comprise a populated stretch of land where L_{den} levels exceed 55 dB due to road traffic noise.
2. An estimate of the number of persons present in the traffic noise environment being considered (e.g. total number of potential receivers affected by a ring road).
3. A characterization of the number of persons living in the vicinity of a given type of road infrastructure (e.g. mean number of potential receivers per kilometre of secondary road in mainland Spain). These data would serve as the basis for large-scale assessments (note that in this case a traffic noise environment is implied).
4. A frequency distribution of noise exposure (typically a histogram of equivalent noise levels L_{den} or the like as calculated at the most exposed façade of dwellings) of persons affected by the traffic noise emission being considered. The availability of these data may be limited, except in those situations where noise maps have been built.
5. Background noise measurements. These data are needed when the system under assessment implies the construction of new road segments in locations where no such infrastructure previously existed (cf. “Large industrial facility” in Table 1). A statistical noise descriptor such as L_{90} may be used for these matters (BS 4142:1997).

2.2.2 Incremental approach to the assessment of noise in LCA

In the proposed methodology, only variations (typically increments) over pre-existing situations are assessed. The adoption of this incremental approach has one major benefit: since sound pressure level variations are fully transmitted along every noise propagation path (Müller-Wenk 1999, 2002, 2004), every receiver in a given traffic noise environment will experience the same increase or decrease in equivalent noise levels after a given NRLV takes place (sound power level increments are also directly translated into sound pressure increments, so no distinction is made between the two). Thus, the incremental approach enables us to overlook propagation conditions in most situations, which saves a great deal of modelling effort. Hence, the incremental approach seems most adequate for the assessment of the impact traffic noise upon human health within LCA.

Let us now take a look at how noise increments (or rather, variations) can be calculated. In the HARMONOISE (2004) and IMAGINE (2005, 2007a, b) traffic noise models, cars are treated as incoherent point sources moving with constant speed along a line which represents a road segment. Assuming this road segment is travelled by a vehicle flow composed of Q vehicles per second sharing the same noise emission characteristics and moving at constant speed v (in m/s), then the mean number of vehicles on the segment at a given instant of time will be Q/v, and the sound power emitted by such a vehicle flow by can therefore be likened to that of a line source continuously emitting the sound power of Q/v vehicles. Hence, the equivalent sound power level per unit length ($L_{\mathrm{eq},T,vehicleflow}$; in dB/m) as emitted by a flow of vehicles of the same class during a time period T can be computed as follows (IMAGINE 2007a):

$$L_{\mathrm{eq,T,vehicleflow}} = L_{\mathrm{vehicle}} + 10 \cdot \log_{10} \frac{Q_{\mathrm{vehicle}}}{v} \tag{2}$$

In Eq. 2, L_{vehicle} is the individual sound power emitted by a single vehicle, Q_{vehicle} is the number of vehicles in the flow being modelled which pass by and v is the mean speed of the flow. L_{vehicle} values, which can be calculated with an appropriate traffic noise emission model (e.g. IMAGINE (2007b)) are associated to a set of input

variables, like vehicle type or class, speed, road surface type and so forth.

2.2.3 Modelling traffic flows

A large numbers of vehicle flows can be modelled to replicate the sound emissions of actual traffic in great detail (e.g. including speed distributions or instant accelerations), but typically only a few flows corresponding to the different vehicle classes will be modelled, and only mean values for speed, rather than distributions, will be considered. To obtain overall noise levels, levels associated to each of the previously modelled flows are summed logarithmically (Eq. 3).

$$L_{\mathrm{eq,T,global}} = 10 \cdot \log_{10} \sum\nolimits_i 10^{Leq,T,vehicleflow,i/10} \quad (3)$$

Note that every vehicle in a single flow thus modelled will share the same characteristics and driving conditions (that is, a common set of traffic noise emission model inputs). The number of classes in which vehicles can be categorized depends on the level of sophistication of the traffic noise model under use. For the sake of simplicity, however, only two classes will be considered in the explanation that follows, namely ‘car’ and ‘truck’. With the aforementioned assumptions, Eq. 3 is thus simplified to:

$$L_{\mathrm{eq,T,global}} = 10 \cdot \log_{10}\left(10^{Leq,T,cars/10} + 10^{Leq,T,trucks/10}\right) \quad (4)$$

2.2.4 Assessment of increases in overall traffic flows

Let us assume for a moment now that the only relevant changes over the initial traffic conditions are simply increases in overall traffic flows (i.e. the total number of vehicles of each class being driven), while the rest of variables remain unchanged. Since vehicle characteristics remain constant, the variations in sound power level for a *vehicle class* caused by a new vehicle flow $Q_{\mathrm{vehicle,\ 1}}$ with respect to a flow $Q_{\mathrm{vehicle,\ and\ 0}}$ may be quickly computed *by subtraction* (Eq. 5).

$$\Delta L_{\mathrm{eq,T,vehicleflow}} = L_{\mathrm{eq,T,vehicleflow.1}} - L_{\mathrm{eq,T,vehicleflow.0}} \quad (5)$$

Eq. 5 can be simplified by incorporating Eq. 2 and applying properties of logarithms:

$$\Delta L_{\mathrm{eq,T,vehicleflow}} = 10 \cdot \log_{10}\left(\frac{Q_{\mathrm{vehicle,1}}}{Q_{\mathrm{vehicle,0}}}\right) \quad (6)$$

Note that these variations *can be computed directly, needless of linear approximations* that would otherwise compromise accuracy. Another interesting quality of this result is that it can be applied in the absence of an emission model, i.e. one does not need to know the initial noise levels or even traffic flows to compute noise level changes due to known traffic flow variations. For example, a 2% increase in the number of ‘car’ vehicles in the road would lead to an increase in noise emission levels of 10·log (102/100)=0.086 dB for the ‘car’ class. The simplicity of this result is owing to the definition of the decibel: equal proportional increases will lead to equal decibel increments. Conversely, equal non-proportional increases in traffic (e.g. one additional vehicle) will lead to different increases depending on initial traffic flows.

Nonetheless, the straightforwardness of the result given in Eq. 6 is obscured in part when classes are summated as per Eq. 3; returning to the previous example, if the noise emission of a car flow were to increase by 0.086 dB (as a result of a hypothetical 2% increase) with the number of trucks remaining constant, the global equivalent level increase would *always* be less than 0.086 dB. Typically, this difference is not very large in absolute terms due the fact that most roads carry more cars than trucks. As a result, most of the sound power emitted comes from cars, not trucks, which means that equivalent levels will be higher for cars (even though the noise emission of a single truck is greater than that of a single car).

A special case of this summation of classes happens when the same proportional increase is attributed to every flow being modelled. In that case, global equivalent levels increase by the same amount—in decibels—as individual class levels (in our example, a 2% increase in both car and truck flows would lead to an overall noise level increase of 0.086 dB). This result may be useful when making rough estimates of global noise level increases due to typical yearly increases in the total number of vehicles on a large road system, which can be likened to small, proportional increases (Müller-Wenk 2002).

2.2.5 Application of advanced traffic noise emission models

We have seen thus far how changes in overall traffic flows can be fast and accurately assessed. However, it would be interesting from the point of view of LCA practice to be able to assess changes (NRLVs) other than mere increases in the number of vehicles travelling on a given road network. This can be accomplished through the implementation of an advanced traffic noise emission model based on the mean sound power emission characteristics of different vehicle classes. As we pointed out earlier, traffic noise emission models reproduce the mean sound emission characteristics of different types (classes) of vehicles in great detail. Mean sound power emissions—under a set of reference conditions—are modelled for each vehicle class as a function of speed. Usually more than one point source is used to model rolling and propulsion noise separately, and all sources are described throughout the audible

frequency range with up to one third octave band frequency resolution. Several correction factors are also modelled to account for variations in noise emission characteristics due to regional variations in vehicle fleet composition or driving conditions. The most relevant corrections available in the IMAGINE model are listed in Table 2. Some of these corrections are not entirely applicable in the context of the assessments we are proposing. This would be the case of meteorological corrections: since they would have to be applied in the same way to initial and final traffic conditions, they would be cancelled in the calculation of variations.

2.3 Selection of a health damage model and calculation of impacts

A health damage model is needed to translate variations in the noise exposure of a population into objective health burdens associated therewith. In the proposed methodology, the impact of traffic noise is characterized by means of changes in the occurrence of self-reported community annoyance, which is linked to L_{den} levels at the most exposed façade of dwellings by means of an appropriate dose–effect relation as explained next. The said dose–effect relation is the basis for a simple calculation method which is also outlined in the following sections.

2.3.1 Dose–effect relations

In Annex III (Assessment methods for harmful effects) of the aforementioned European Noise Directive, it is stated that 'dose-effect relations should be used to assess the effect of noise on populations'. Two sets of such dose–effect relations for noise emitted from traffic and transportation have been agreed upon by the European Commission Working Group on Health and Socio-Economic Aspects. The first of these sets is meant for assessing annoyance caused by road, rail and air traffic noise using the L_{den} metric (EC 2002) and is the base for the impact calculation procedure explained in Section 2.3.3. The second set is used for assessing sleep disturbance using L_{night} (EC 2004).

2.3.2 Annoyance as an indicator for the health impacts of traffic noise

In previous methodologies aimed at assessing road transport noise within LCA (Doka 2003; Müller-Wenk 1999, 2002, 2004), the impacts were totalled in terms of DALY. However, the benefits of this approach—a solid conceptual framework for DALY units, the possibility of aggregation with other health-related impacts—are somewhat diluted when dealing with noise, partly due to the unique characteristics of noise as a pollutant: unlike CO_2; for instance, noise emissions ought to be attached to particular spatial and temporal coordinates in order to become truly meaningful. Moreover, the different attitudes of receivers towards noise are a relevant input that should be factored in. This double dependency—for site and receivers—arguably justifies the adoption of a particular treatment within LCA. It also has major implications in the selection of indicators. Self-reported community annoyance is proposed herein due to the following reasons:

- *Prevalence*: Of all health effects of environmental noise described in the literature, annoyance—followed by sleep disturbance—is the most widespread (EuP 2002; WHO 1999).
- *Quality of dose-response functions*: While the relationship between annoyance and environmental noise seems solidly established, the same cannot be said about other non auditory health effects (Babisch et al. 2005; Maschke et al. 2002).
- *Antecedence/concomitance with other impacts*: Noise acts as an environmental stressor (Miedema 2007) with effects ranging from mild annoyance to increased risk of myocardial infarction. As far as the more severe effects are concerned, causality links are difficult to establish because they are usually the consequence of a large number of factors (not only environmental, but also genetic or behavioural) which are difficult to isolate (Job 1997). It seems plausible, however, to assume that there is a certain relationship of antecedence and concomitance between annoyance (and also sleep disturbance) and the more severe health effects of environmental noise. Annoyance precedes the onset of the more serious health effects and accompanies them; it could hardly be argued, e.g. that an individual whose immune system were significantly affected by environmental noise would not report to be annoyed by noise. Annoyance could be thought of as a proxy indicator (a 'signal flag') for more severe health effects. Also, by choosing an indicator that measures one of the lesser—yet the most widespread and thoroughly described—consequences of exposure to environmental noise, a conservative, preventive stance is built into assessments.
- *Intelligibility:* Since noise annoyance is so commonly experienced, it is much more easily understood by non-experts than the complex rationale behind DALY units, thus rendering it a valuable indicator to support decision making or present assessment results to the general public.
- *Comprehensiveness*: As seen from Eq. 1, the sound pressure level during the evening period is penalised by 5 dB and the level at night by 10 dB. In this way, the 'psychological' increase of the impact of noise during the night and the evening is taken into account to some extent.

Table 2 Corrections in the IMAGINE model (IMAGINE 2007b)

Correction type	Corrections	Application to the proposed assessment method
Regional corrections	Engine type (Otto/Diesel) tire width vehicle age	Assessment of variations in several vehicle fleet characteristics, as appropriate
Meteorological corrections	Ambient temperature wet road surface	Not applicable
Correction for driving conditions	Instant acceleration	Increased accuracy in small-scale assessments (esp. urban environments)
Correction for road surface	Road surface	Assessment of 'silent' road surfaces

2.3.3 Impact calculation procedure

The method for the final calculation of impacts is based on the polynomial approximations of the dose–response curves relating L_{den} levels at the most exposed façade of dwellings and self-reported annoyance found in (Miedema and Oudshoorn 2001), which are provided in Table 3. Separate curves exist for the percentage of highly annoyed, annoyed and lowly annoyed persons (%HA, %A and %LA, respectively), but typically only %HA curves would be used.

The calculation of impacts is as simple as the subtraction of the estimated percentage of annoyed persons at L_{den} levels attributed to initial traffic conditions from those due to final traffic conditions, thus yielding variations in annoyance (typically increments). These variations in the percentages of annoyed persons are then multiplied by the number of estimated receivers to yield the additional number of annoyed persons. When a histogram describing the exposure of the population to traffic noise is available, the equations can be applied in the midpoint of the existing intervals (this was applied in Table 4 for two hypothetical L_{den} increases of 0.1 and 1 dB, and it is also the calculation procedure in the methodology application example found in Section 2.4). In situations where the frequency distribution of noise exposure is lacking, approximations can be derived from the polynomials (e.g. %HA increases approximately 2.2% per decibel between 45 and 75 dB).

2.3.4 On the linearity of impacts of additional vehicle-kilometres

The special relevance of spatial data in the assessment of noise has been pointed out earlier. Some additional commentary is given next to exemplify how this circumstance affects the inclusion of noise within LCA: let us suppose that we were to assess the impact of the exhaust gas emissions of 1,000 cars being driven for 1 km each (that is, of 1,000 vehicle-kilometres) in any of the customary LCA impact categories (e.g. in the acidification category). This impact would be approximated as the product of the number of vehicle-kilometres driven by a constant factor (i.e. $1{,}000 \cdot k_{\mathrm{acidification}}$). If an undetermined number of additional cars n_{cars} were to be driven for a given number of kilometres n_{km}, the additional impact would be simply calculated as $n_{\mathrm{cars}} \times n_{\mathrm{km}} \times k_{\mathrm{acidification}}$. However, due to the logarithmic nature of the units commonly used to measure noise (decibels), this same approach cannot be taken without sacrificing accuracy; in short, no factor can be calculated to be applied in any situation, and some spatial data has to be incorporated into the assessment.

The following hypothetical situation may illustrate the previous point: imagine one road segment that is travelled

Table 3 Polynomial approximations of the synthesis annoyance curves extracted from (Miedema and Oudshoorn 2001)

Annoyance curve	Polynomial approximation
Percentage of highly annoyed (%HA)	$9.868\times10^{-4}\ (L_{\mathrm{den}}-42)^3-1.436\times10^{-2}\ (L_{\mathrm{den}}-42)^2+0.5118\ (L_{\mathrm{den}}-42)$
Percentage of annoyed (%A)	$1.795\times10^{-4}\ (L_{\mathrm{den}}-37)^3+2.110\times10^{-2}\ (L_{\mathrm{den}}-37)^2+0.5353\ (L_{\mathrm{den}}-37)$
Percentage of lowly annoyed (%LA)	$-6.235\times10^{-4}\ (L_{\mathrm{den}}-32)^3+5.509\times10^{-2}\ (L_{\mathrm{den}}-32)^2+0.6693\ (L_{\mathrm{den}}-32)$

upon by a constant flux of one thousand vehicles of equal characteristics per hour (Scenario a in Table 5). Let us suppose this flow leads to an hourly equivalent noise level of 55 dB at a selected reception point (e.g. the façade of a dwelling), and estimate that the total elimination of traffic would lower this level to a background level of 45 dB. Table 5 shows what impacts would be observed if traffic were to increase by one (Scenario b) and by one hundred additional vehicles per hour (Scenario c).

Table 5 is intended to illustrate two different phenomena. The first one—which is widely known—is the non-linearity of the summation of noise sources (see Eq. 3), which translates into a decrease in the impact of equal amounts of additional vehicles with increasing initial (baseline) traffic levels (observe how, in row E, additional vehicles per hour for Scenario c only have 91% of the impact of those for Scenario a). This means that linear approximations (i.e. calculations of overall noise increments performed as the sum of small, fixed increments attributed to vehicles or vehicle-kilometres) lead to appreciable levels of inaccuracy when traffic levels depart significantly from whichever levels were taken as a baseline. This is not a big concern in cases like the one illustrated in the example (see Section 2.4), where only a small increment from baseline traffic is assessed. However, the results of this type of assessment cannot be extrapolated to other situations where larger variations would be involved. These would thus have to be computed separately under new calculation assumptions. Fortunately this represents only a minor hassle once the nose emission model has been set up.

The second phenomenon—and perhaps the more relevant of the two—can be expressed as warning: whenever an incremental approach is taken in the assessment of noise impacts, those impacts caused by baseline traffic are conceptually left out of the assessment and therefore implicitly accepted. This clarification is especially pertinent because, by virtue of the logarithmic law of impact increases, the mean impact of baseline traffic will always be higher than that of additional traffic (and significantly so; see Table 5, rows G and H). This implies that the impact calculated for additional vehicle-kilometres cannot be used to extrapolate the impact of all vehicle-kilometres driven during a time period in a given territory, because it will lead to a large underestimation global impact figures. In other words: the incremental approach is valid for LCA (assessment of variations, be it large or small), not for environmental impact assessment (assessment of the impact of road transport noise as a whole).

2.3.5 Expression of results and assessment documentation

The final stage of the proposed method is the expression of results and the documentation of the assessment. As implied from the previous section, special care is needed when defining the scope and expressing the results of traffic noise assessments so that the applicability of results is clearly stated and impacts are attributed solely to the NRLVs included in the assessment.

2.4 Application example

An application example (based on the methodology presented and using real traffic and noise exposure data made available by the Spanish Government pursuant to Directive 2002/49/EC) is proposed. For the sake of simplicity, the impact of a generic trip of 1,000 km is assessed, although the methodology can be readily tuned to assess a large variety of trips. The example includes all the calculations strictly relevant to noise emissions and its impact in terms of increased annoyance.

Table 4 Example calculations using synthesis annoyance dose–response functions

L_{den} (5-dB interval midpoint 45~75dB)	47.5	52.5	57.5	62.5	67.5	72.5
%HA at L_{den}	21.288	31.501	42.551	53.971	65.293	76.049
%HA at L_{den} +0.1 dB	21.481	31.715	42.777	54.200	65.515	76.255
Δ%HA'/ΔL_{den}	1.930	2.144	2.263	2.290	2.222	2.061
Mean Δ%HA'/ΔL_{den}	2.152					
%HA at $L_{\mathrm{den}''}$ +1 dB	23.439	33.876	45.048	56.486	67.724	78.293
Δ%HA/ΔL_{den}	2.151	2.376	2.497	2.516	2.431	2.244
Mean Δ%HA"/ΔL_{den}	2.369					

Table 5 Variations in noise impacts across different baseline levels. Impacts of additional traffic vs. baseline traffic

Indicator	Calculation method	Scenario a	Scenario b	Scenario c
Number of vehicles per hour (A)	-	1,000	1,001	1,100
Background noise at reception point [dBA] (B)	-	45	45	45
Noise level at reception point [dBA] (C)	$55+10\cdot\log_{10}(A/1{,}000)$; cf. Section 2.2.4	55	55.0043	55.4139
Mean impact per vehicle per hour; as equivalent noise level increase (D)	$(C-B)/(A)$	0.01	0.00999	0.00947
Impact of one additional vehicle per hour; as equivalent noise level increase; baseline=A (E)	$10\cdot\log_{10}((A+1)/A)$	0.004341	0.004336	0.003946
Mean impact of additional traffic; as equivalent noise level increase; baseline=1,000 vehicles (F)	$10\cdot\log_{10}((A/1000))/(A-1000)$	-	0.004341	0.004139
Mean-to-additional impact ratio; as equivalent noise level increase; baseline=A (G)	D/E	2.304	2.305	2.399
Mean-to-additional impact ratio (as equivalent noise level increase; baseline=1,000 vehicles) (H)	D/F	-	2.302	2.287

From these results, further attribution of impacts to specific functional units or life cycle stages of products should be a straightforward procedure for LCA practitioners.

In the calculation example proposed (which is also an example of how traffic noise assessments should be documented, as described in Section 2.3.5), the impact of a single 1,000-km trip taken by a heavy-duty vehicle is calculated (the trip itself would therefore be the NRLV under consideration, this is akin to case "Product or service that involves some form of road transport along its life cycle" in Table 1). The traffic environment would be the surrounding area along the 1,000 km of roads where the trip takes place. The general assumptions for the calculations are as follows:

- The trip takes place only once exclusively on high-capacity roads. Said trip directly contributes to increasing the total of vehicle-kilometres travelled on high-capacity Spanish roads by 1,000 units (other types of roads could be included in the calculations, but were left out for the sake of simplicity).
- The initial traffic flows considered are extracted from (MFOM 2007). The traffic flows are allocated to the periods of the day in the same fashion as in (Garraín 2009). The mean number of affected persons per kilometre of high-capacity road and the noise exposure distribution of receivers are extracted from (MFOM 2008).
- The IMAGINE model (IMAGINE 2007a, b) is used to compute acoustic power emissions. Traffic is composed of a mix of category (CAT) 1 (light vehicles; corresponding vehicle category in EU/ECE type approval: M1 and N1), CAT 3 (heavy vehicles; M2 and N2 with trailer, M3 and N3) and CAT 4b vehicles (motorcycles, tricycles or quads with engine capacity above 50 cm^3; L3, L4, L5, L7). For the sake of simplicity, none of the corrections mentioned in Section 2.2.5 of the article were applied. This should have negligible influence on the final results.
- Impact calculations are based upon the polynomial approximation to the dose–response annoyance functions found in (Miedema and Oudshoorn 2001). No translation of annoyance into DALY units is performed.

The calculations are divided in two parts: first are the calculations to obtain the variation in L_{den} in the environment under consideration due to the additional trip, and in the second part, the increased annoyance due to said variation in L_{den}.

2.4.1 Calculation of the variation of L_{den}

Emission data The individual mean acoustic power emission of the considered vehicle categories is computed using

the IMAGINE model (IMAGINE 2007a, b). The mean speeds by vehicle class considered in the computation are extracted from (MFOM 2007;Table 6).

Using traffic data to compute variations in L_{den} The additional 1,000 vehicle-kilometres are allocated to the periods of the day based on the assumptions found in (Garraín 2009). This leads to a small increase in the flow of CAT 3 vehicles, which in turn causes an increase of the acoustic power emission of the road segments considered. These are computed through the implementation of the IMAGINE model (IMAGINE 2007a, b) in spreadsheet software (Table 7).

2.4.2 Annoyance calculations

Calculating increased annoyance from dose-response curves The mean increments in the number of highly annoyed persons (Table 8) are approximated by differentiating the polynomial approximation of the annoyance curves found in Miedema et al. (2003) at the midpoint of the exposure interval considered (e.g. for the 55–59-dBA interval, the increased annoyance is calculated at 57 dBA) and multiplying by the calculated L_{den} (see Eq. 7).

$$\Delta\%\mathrm{HA} \approx \frac{\mathrm{d}\%\mathrm{HA}(L_{\mathrm{den}})}{\mathrm{d}L_{\mathrm{den}}} * \Delta L_{\mathrm{den}} \quad (7)$$

Coupling dose–response functions to exposure data Exposure data are for high-capacity Spanish roads are extracted from MFOM (2008; Table 9).

From the data in Tables 8 and 9, the calculation of the number of additional highly annoyed population is quite straightforward, as it is a mere multiplication of the number of exposed population per kilometre of road, the mean increment in number of highly annoyed people and the trip's length in kilometres. These results are given by noise-exposure class, but can be directly summated (Table 10).

The final result thus indicates that the considered trip causes an increased annoyance of roughly 1.526E-3 additional persons for the given year, since the trip contributes to increase yearly traffic flows and yearly L_{den} values. For small variations in overall traffic flows like the one considered, and as long as the baseline traffic flows remain unchanged, it can be estimated that the increased annoyance due to heavy-duty vehicles is 1.526E-6 additional persons per vehicle-kilometre. Performing the calculations in a similar fashion for light-duty vehicles (CAT 1) yields a result of 1.336E-6 additional annoyed persons per vehicle-kilometre driven.

Table 6 Individual mean acoustic power emissions of the considered vehicle categories

IMAGINE model vehicle category (IMAGINE 2007a)	Mean speed (km/h)	Mean speed (m/s)	Individual acoustic power emission at mean speed considered (W)
CAT 1	102	28.33	3.8534E-02
CAT 3	80	22.22	3.4521E-02
CAT 4b	102	28.33	2.9659E-02

3 Results

The general framework of a method to assess the impact of traffic noise upon human health within LCA has been presented. This method, which finds its basis in the work of Müller-Wenk, can be used to evaluate a large number of variations in traffic other than mere increases in overall traffic flows. Reasonably good estimates of equivalent noise level increases due to proportional increases over pre-existing traffic have been found without using a noise emission model (cf. Section 2.2.4). In order to assess other types of changes affecting traffic noise emissions, the concept of NRLV has been proposed as the link between the system under assessment in LCA and the advanced traffic noise emission models which allow us to translate the effect of the system into equivalent noise level increases experienced by receivers in a given traffic noise environment. In this way, only the variations attributable to the system under assessment are taken into account in the assessment. A simple calculation method to translate these variations into health impacts has been outlined using an appropriate health damage model based on a dose–response model relating L_{den} levels at the most exposed façade of dwellings and self-reported annoyance.

An application example of the proposed methodology was provided in Section 2.4. The calculations are supported by a state-of-the art emission model (which is used to compute the necessary LCIA dataset), and by high-quality data regarding vehicle flows and noise exposure levels. These data are made available and periodically updated by EU member states as established in (EuP 2002).

4 Discussion

Noise may well be one of the largest issues affecting human well-being and yet it is largely ignored in everyday LCA practice. The proposals presented herein seek to help overcome the methodological shortcomings that have prevented the inclusion of traffic noise within LCA.

Table 7 Calculation of variation in L_{den}

Period of the day	Day	Evening	Night	Total
Network length; km (MFOM 2007)	13,872	13,872	13,872	
Mean flow CAT 1; vh/s (MFOM 2007)	0.484827595	0.15290442	0.075774379	
Initial mean flow CAT 3; vh/s (MFOM 2007)	0.08207277	0.025884025	0.012827267	
Mean flow CAT 4b; vh/s (MFOM 2007)	0.042158921	0.013296037	0.006589076	
vkm CAT 1	1.06E+11	1.11E+10	1.10E+10	1.28E+11
vkm CAT 3 (initial)	1.80E+10	1.89E+09	1.87E+09	2.17E+10
vkm CAT 4b	9.22E+09	9.69E+08	9.61E+08	1.12E+10
Percentage vkm CAT 1, (%)	82.69	8.69	8.62	100.00
Percentage vkm CAT 3, (%)	82.69	8.69	8.62	100.00
Percentage vkm CAT 4b, (%)	82.69	8.69	8.62	100.00
Δvkm CAT 3	826.9105955	86.93006653	86.15933798	1,000
Δflow CAT 3 (vh/s)	5.24E-08	1.65E-08	8.20E-09	
Final mean flow CAT 3 (vh/s)	8.21E-02	2.59E-02	1.28E-02	
Initial acoustic power emission of combined vehicle flows $W_{initial}$ (W/m)	8.3100248E-04	2.6208069E-04	1.2987853E-04	
Final acoustic power emission of combined vehicle flows W_{final} (W/m)	8.3100256E-04	2.6208072E-04	1.2987855E-04	
Increment in acoustic power emission level of combined flows $\Delta L_{w\ vehicle\ flow}$ [dBA/m][a]	4.2575E-07	4.2575E-07	4.2575E-07	
ΔL_{den} (see Eq. 1)				4.2575E-07

[a] Computed increments are equal because they are proportional to initial flows; see Section 2.2.4

The incremental approach—as first applied by Müller-Wenk—seems most adequate for the assessment of the impact of traffic noise upon human health within LCA, since it allows overlooking noise propagation conditions in most situations. However, some caution needs to be exercised before applying it to non large-scale assessments, where site-dependency dominates and the assumption of linearity can significantly distort its results. To that avail, a more accurate calculation method has been proposed. This method is supported by the advanced traffic noise emission model IMAGINE. However, no special endorsement of said model is made; any other comparable model could be used, for example (Jonasson and Storeheier 2001).

The special characteristics of noise as a pollutant demand a bespoke approach to its assessment. Performing the attribution of the health impacts of traffic noise through generic characterizations of vehicle-kilometres—whether additional or not—may mask the true responsibility of traffic for increasing noise levels, and is therefore advised against. Rather than providing generic impact factors, impacts are attributed to NRLVs, whose relation with the system under assessment will have been properly justified in the assessment documentation.

In (Althaus et al. 2009b), a proposal for context-sensitive modelling of road transport noise emissions (not its impacts) is made, but this is based on a somewhat dated model and lacks scalability. The methodology proposed herein allows for a scalable (because it can be adapted in function of the availability of data and is applicable to traffic variations other than mere increases in the number of vehicle-kilometres travelled), complete (because it effectively couples a variation in traffic conditions to its health effect) and context-sensitive assessment of road traffic noise. Furthermore, it identifies a consistent data framework for the evaluation of its impacts with ample institutional support.

The immediate applicability of the methodology with existing tools and presently available data is demonstrated with a calculation example in Section 2.4. The said application example highlights a key advantage of using a acoustic power type of model instead of one based on measured sound pressure levels (Müller-Wenk 2002, 2004; Althaus et al. 2009b), which is that sound power is linearly additive, making it an ideal parameter to build the required LCI dataset. However, it must be taken into account that

Table 8 Mean increments in number of highly annoyed persons (Δ%HA)

Mean increments in number of highly annoyed persons Δ%HA	
Δ%HA (55–59 dBA)	3.127E-07
Δ%HA (60–64 dBA)	4.679E-07
Δ%HA (65–69 dBA)	6.849E-07
Δ%HA (70–74 dBA)	9.638E-07
Δ%HA (>75 dBA)	1.305E-06

Table 9 Noise level exposure distribution data

L_{den} (dBA)	(55–59)	(60–64)	(65–69)	(70–74)	>75	Total
Exposed population by kilometre of road	190,082	93,346	38,753	15,819	5,922	343,921

sound power emission values (in Watts) are a function (among others) of vehicle class and speed. Therefore, they need to be computed for every specific case, as do increases in equivalent emission levels (in dBA), because they depend on the initial traffic situation. Fortunately, these computations are easily performed once the emission model is implemented in a suitable software application (note that in the proposed calculation example, the IMAGINE model was implemented in spreadsheet software).

The results from the calculation example are plausible. In Müller-Wenk (2002), a similar calculation was performed for an additional 1,000-vkm trip in Switzerland. The results are not directly comparable because in Müller-Wenk (2002) the trip takes place during the daytime only and on several types of roads, but their comparison is nonetheless interesting. Müller-Wenk computed an increased L_{Aeq} of 5.00E-7 dBA, while our results yield an increase of 3.80E-7 dBA in L_{den} values. As far as calculated impacts are concerned, Müller-Wenk estimated 3.8E-2 additional cases of communication disturbance (which can be likened to annoyance), while our results point to roughly 1.3E-3 additional cases of annoyance. This may be due to the fact that the exposed population considered by Müller-Wenk was 3.36 million, while in our case it was about 344,000 persons (as extracted from strategic noise map data).

5 Conclusions

The methodological proposals presented herein may be of assistance to support a wide variety of traffic noise assessments within LCA, its applicability not being limited to large-scale assessments.

The use of state-of-the-art vehicle noise emission models should allow for more accurate assessments that dispense with linear approximations. The application of such models requires that sufficient data regarding the spatial distribution of receivers and traffic characteristics (traffic flow, average speed per vehicle type and so forth) are known.

The special characteristics of noise as a pollutant (relevance of spatial data, human perception issues) appear to justify the adoption of a distinct indicator, namely 'number of annoyed persons'. Incorporating annoyance as the preferred indicator for the impact of traffic noise upon human health is thought to make assessment results more intelligible and readily applicable to decision making in matters like infrastructure policing and urban planning, whilst placing the focus on damage prevention. Moreover, the adoption of standard dose–response relations between self-reported annoyance and L_{den} levels can be expected to lower the uncertainty of this type of assessments, while the endorsement of L_{den} by the European Commission for noise mapping purposes is certain to improve the availability of the quality data they require.

6 Recommendations and perspectives

The use of 'number of annoyed persons' instead of DALY units is favoured because it allows for a more straightforward presentation of results, even if it excludes the possibility of aggregation with other health impacts. Nevertheless, the use of DALY is not excluded beforehand. Neither is the inclusion of other health impacts attributable to noise, insofar as a scientifically sound relationship between long-term exposure to environmental noise and other health conditions is agreed upon by medical experts. In particular, the assessment of sleep disturbance using L_{night} noise exposure levels by means of the dose–response relation found in (EC 2004) could be included with minor methodological adjustments.

In this paper, only road traffic noise is dealt with. However, annoyance curves with a comparably solid

Table 10 Additional highly annoyed population due to the trip under consideration

Additional highly annoyed population [increased highly annoyed persons]	
HA (55–59 dBA)	5.943E-04
HA (60–64 dBA)	4.368E-04
HA (65–69 dBA)	2.654E-04
HA (70–74 dBA)	1.525E-04
HA (>75 dBA)	7.725E-05
Total additional HA	1.526E-03

scientific background also exist for railway and aircraft noise, which would make comparisons between alternative transportation modes feasible. The adoption of L_{den} as the primary common noise descriptor for noise mapping should also help incorporate environmental noise from industrial sources into LCA.

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